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Stormwater Retention for a Modular Green Roof Using Energy Balance Data

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SUMMARY OF KEY FINDINGS

New York City stormwater is a major cause of water pollution in the harbor and estuaries. This is due to the vast areas of impervious surfaces (e.g., rooftops, pavements, sidewalks) that rapidly shunt runoff into the combined sewage overflow (CSO) system. Green, vegetative roofs may offer one of the most effective methods of distributed stormwater control to help abate this pollution. We have analyzed data from an experimental modular green roof system on the Con Edison "Learning Center" in Long Island City, New York. From the first year of data we report the following key findings:

- **Evaporation of water from a green roof (referred to scientifically as "evapo-transpiration" or "latent heat loss") is equivalent to water that is retained by the green roof and never enters the municipal stormwater runoff system or wastewater treatment facilities.**
- **Using field data on net surface radiation, net heat conduction from the building below, and net surface convection, we have been able to estimate net annual and seasonal stormwater retention on the Con Edison green roof. This calculation is a "surface energy balance" analysis.**
- **We estimate that the green roof was retaining ~30 percent of the *annual* rainfall and snowfall water volume incident upon it.**
- **During the *summer* we estimate that the green roof was retaining ~35 percent of the rainfall incident upon it.**
- **In terms of gallons of water retained per square foot of roof, we estimate that the green roof was retaining ~10.2 gallons/square foot (f^2) annually and ~4.4 gallons/square foot during the summer season. Thus 43 percent of the annual retention took place during the summer season when the plants were active.**
- **The annual stormwater retention rate determined from this project is a factor of ~22 times greater than that assumed in the New York City PlaNYC 2008 Stormwater Management Plan Report for green roofs. The low retention rate assumption in that report (0.47 gallons/f^2), combined with other assumptions, led to an unfavorable CSO cost-benefit ranking for green roofs. Our retention correction alone could change the green roof ranking in the PlaNYC report from least cost-effective to the *most* cost-effective of the interventions considered.**
- **The retention on this modular green roof is significantly less than what we have estimated on a comparable built-up (continuously layered) green roof we have studied, which is showing ~50 percent retention. This may be due to the modular nature of this green roof system, which may have a reduced medium volume and horizontal water flow because of gaps and tray boundaries.**
- **Assuming New York City has approximately 1 billion square feet of roof surface area, our study suggests that 10–15 billion gallons of annual rainfall would be retained if all this area were covered with a 4-inch sedum-based green roof layer.**
- **The detained water that does runoff the green roof will have a secondary positive effect on combined sewage overflow (CSO) mitigation, by delaying the peak flows.**

Introduction

One of the most important environmental benefits of green/vegetated roofs is their potential for reducing stormwater runoff—in stark contrast to traditional waterproof roofing membranes. This is due primarily to the presence of a growth medium that mimics real soil both in allowing properly selected plants to thrive and also providing a porous volume capable of holding soil moisture. In many ways, the real goal of green roofs is to reintroduce the essential properties of soils into urban areas—soils that have been all but paved or built over with urban development. We have in effect disconnected the urban environment from the benefits of its original soil and vegetation layers.

In the preface to his seminal textbook on soil physics, Daniel Hillel,[1] a co-author on this report, regales readers with fascinating, underappreciated facts about soil and humanity, including: (i) a mere fistful of soil contains several acres of particulate surface area performing essential natural processes; (ii) we treat soil with disdain, referring to it as "dirt" and inculcating children to wash their "soiled" hands, yet it is the land's principal medium for purification and decomposition of wastes; (iii) the biblical name for the first human Adam derives from the Hebrew word for soil and the latin name for the human species, Homo, derives from humus, the material of soil; (iii) soil is an exceedingly thin sphere on Earth, typically no more than a meter thick and often less, yet it is the "crucible" of all terrestrial life.

And, significantly for this report, Hillel also offers the following observation about soils: "*…without the soil as a buffer, rain falling over the continents would run off immediately, producing violent floods rather than sustained stream flow.*"

Indeed, modern cities, with their vast areas of impervious pavements, sidewalks, and rooftops, are a real-world experiment testing this observation. Were it not for the drains that are placed everywhere at street and rooftop levels to prevent flooding at these surfaces, we indeed would see such "violent floods" during and after a rain. Instead, the drains merely shift the floods into pipes underground. Moreover, a standard practice in urban infrastructure is, unfortunately, to combine this stormwater flow with the flow from building water use, including sanitary and other wastewater.

The result is a combined sewage and rainwater flow that is supposed to end up at wastewater treatment facilities. However, with even moderate rains, the volume of water floods the system—confirming Hillel's thought experiment—and the excess water is then shunted into surrounding waterways, as an emergency measure to prevent it from backing up into streets and elsewhere. The result is a combined sewage overflow or CSO that is the bane of our urban coastal environment. The liquid components of building sanitary water (e.g., toilets) and other wastes thus pollute waterways, leading to many adverse impacts, including the familiar beach closings.

Thus the unintended consequence of our relentless practice of paving or building over soils, as if they were of no importance to us, is a critical and growing CSO problem.[2] Clean waterways should be a reliable source of drinking water, food potential, recreation, and ecological habitat. CSOs prevent much of this.

One obvious solution is to re-expose urban soils to rainfall, and to the extent this possible at street level, it is one strategy that is

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[1] D. Hillel, *Introduction to Environmental Soil Physics*, 2004, Elsevier Academic Press, Amsterdam, 494 pages.

[2] C. Duhigg, "As Sewers Fill, Waste Poisons Waterways," *New York Times*, November 22, 2009; M. Navarro, "$1.5 Billion Plan Would Cut Sewage Flow Into City Waters," *New York Times*, September 28, 2010.

being pursued. Parks, street tree pits, "greenstreet" projects that reintroduce vegetation and expose soil at street level can all be seen in this light. Porous pavement is an intriguing new technology that is being studied and tested.[3] Other rainwater collection systems are also being researched and developed, including storage tank systems, bio-retention and infiltration basins, among other concepts.

A remaining key land area component is clearly rooftops. Often comprising 10%–20% or more of urban landscape, cumulative rooftop space is an enormous untapped area for significant stormwater control. Or rather, cumulative impervious roof space is a leading contributor to CSOs. The solution here is similar—reintroduce soil to the extent possible.

Given the need for minimal weight load on standard rooftops, true soil is not ideal. Fortunately, the technology of green roof science has mastered lightweight engineered growth media, with water storage capacity similar to soils.[4]

In this report we quantify that storage capacity for a modular green system installed on the Con Edison Learning Center.

The Con Edison "Learning Center" Modular Green Roof System

Figure 1. Photograph of the green roof modular system after one year showing above-grade monitoring stands

The modular (tray modules) green roof system that we study is shown in **Figure 1**. It is from GreenGrid[5] and consists of a 4-inch mineral growth medium and planted with a palette of sedum vegetation.

Also visible in the picture are two sensor stands holding above-grade monitoring equipment that are key to our stormwater control analysis. The stand on the left holds an "allwave" radiometer that measures the net flux of radiant energy (net shortwave plus net longwave) absorbed by the roof. The stand on the right is holding standard weather station sensors, including ambient air temperature, relative humidity, and wind speed and direction sensors.

Rainfall (water) incident upon any roof surface, be it green or not, has two long-term fates. Eventually, it must either: (i) run off the roof as liquid water and into the local watershed system or (ii) return to the atmosphere as water vapor. Although a volume of water is present on a green roof in the form of "soil" moisture and in the plant biomass, over the long term this

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[3] B.K. Furgeson, "Porous Pavements," in S.W. Trimble, B.A. Stewart and T.W. Howell (eds.), "*Encyclopedia of Water Science,* 2nd Edition," 2007, CRC Press, Boca Raton, 1586 pages.

[4] See, for example: E.C. Snodgrass and L. MacIntyre, *The Green Roof Manual: A Professional Guide to Design, Installation and Maintenance*, 2010, Timber Press, Portland, 295 pages.

[5] www.greengridroofs.com/greenroofs.htm.

volume is always limited, finite and small compared to the cumulative flows of rainfall, runoff, and vaporization.

Water that is returned to the atmosphere as vapor, and so does not enter the sewer system, is referred to as “retention.” Water that flows from the roof as runoff is referred to as “detention.” This terminology can be intuitively understood in terms of the childhood school disciplinary experience of being “sent to the principal’s office for detention.” In this case, you are *temporarily* confined to the principal’s office but eventually released. Retention would be the (unthinkable) experience of never being released. In this report, retention and detention will be quantified as percentages of incident rainfall and volumes of water (e.g., gallons) over fairly long periods of time, such as annually or seasonally.

From the perspective of the CSO problem, rainfall that is retained is the most desirable and environmentally beneficial, as this water never enters the wastewater processing system. (In addition this water vapor is responsible for the cool temperatures on green roofs that help mitigate heat islands and building-energy needs.) But detained water is also beneficial in helping reduce the CSO impacts—by delaying the release of runoff, the peak flow to the wastewater treatment system is also reduced.

A diagram of the water “budget” on a green roof is shown in **Figure 2**.

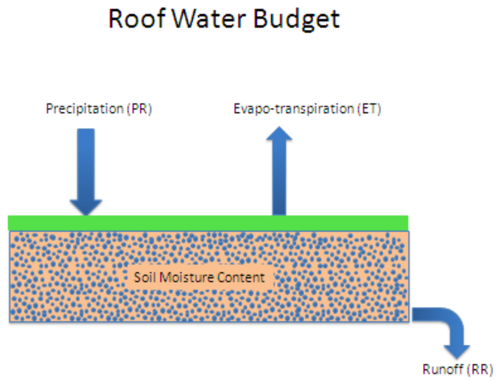

Figure 2. Diagram of green roof water budget

The diagram depicts three arrows and one reservoir. The three arrows are: (i) precipitation (including rain, snow, dew, hail, fog-related condensation); (ii) runoff into drains on the roof; and (iii) evapo-transpiration, which is water vapor due to evaporation from the soil and plant surfaces and water vapor release from the plant leaves (transpiration). The reservoir is water stored in the medium as soil moisture. This water is essential to plant survival and also to the long-term cooling effect of green roofs.

Since the soil moisture reservoir is always finite and limited, when we consider the cumulative amounts of rainfall, over say months or years, the soil moisture content is negligible to such cumulative volumes, and the water budget simplifies to the following simple relationship:

$$\textit{cumulative precipitation} \cong \textit{cumulative retention} + \textit{cumulative detention} \qquad (1)$$

This equation simply expresses the physical fact that over the long term, all rainwater must eventually leave the green roof system either as evaporation (retention) or runoff (detention). It also means that if we know the cumulative rainfall, from a rain gauge, and if we can determine the cumulative retention, then we know the detention, too, as the remaining volume.

Determining Water Retention Using Energy Balance Considerations Alone

In this report, we determine the water retention using a novel method that may not have been attempted before for green roofs. It will be determined from data on the surface energy balance of the roof alone. The primary reason we do this is necessity: the scheduling of the project during the first year did not allow us to install direct flow meters into drains. Such meters are being installed during the writing of this report. However, the determination of water retention from energy considerations is a sound scientific approach and is of research and technical interest in its own right.

Energy balance refers to the flows of energy and storage for any physical object. It is quite analogous to the water balance just described, except it is in terms of energy and energy storage. A diagram of energy balance for a green roof layer is shown in **Figure 3**.

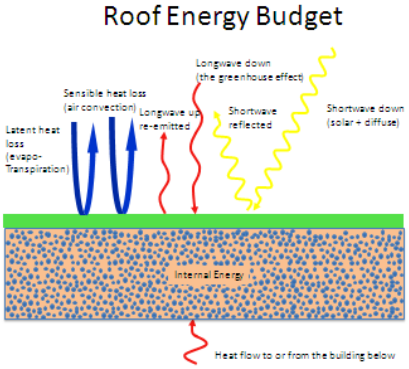

Figure 3. Diagram of green roof energy budget

Considering the green roof test volume to be that from the top of the plants to the bottom of the growth medium, there are seven major fluxes of energy and one reservoir of energy. The seven fluxes are (i) incident sunlight; (ii) reflected sunlight; (iii) absorbed atmospheric thermal radiation; (iv) emitted green roof surface thermal radiation; (v) convective heat loss or gain from the atmosphere; (vi) conductive heat loss or gain from the building below; and, finally, (vii) evapo-transpired energy in the form of water vapor.

Evapo-transpired energy is often given the acronym ET in scientific literature. It is also commonly referred to as “latent heat” loss. The term ‘latent’ is meant to convey the fact that the energy it represents results from a phase change from liquid to vapor water, rather than a temperature increase. Latent heat is a more generally useful term for referring to this energy flow because such heat loss occurs on nonliving surfaces as well, wherever water or soil moisture is present (e.g., lakes, oceans, wet non-vegetative roofs, boulders, etc.).

In the plant and animal kingdoms, latent heat is one of nature’s most powerful mechanisms for thermal regulation. We experience this energy loss in ourselves as perspiration, which the human body induces so that the liquid water on our skin can evaporate and thus carry heat energy away as needed for thermal homeostasis.

Plants generally have large water requirements. Often well over 90% of this water is transmitted to the atmosphere as transpiration.[6] The exact reasons for such high water transmission and demand remain a subject of scientific inquiry, with direct importance for agriculture. However, a likely partial explanation for this is thermal regulation. Green

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[6] Hillel, An Introduction to Environmental Soil Physics, page 365.

leaves are relatively dark surfaces with respect to sunlight reflectivity. If they were inanimate, such dark surfaces would reach extremely high temperatures in strong sunlight, similar to the temperature increases on dark pavements, or rooftops.

Interestingly, synthetic recreation fields are an experimental test of this, since they are designed to have the dark colors of grasses but are inanimate and dry. It has recently become apparent, as shown in work by the PI, that such artificial fields are indeed problematic heat sources during recreation in strong sunlight.[7]

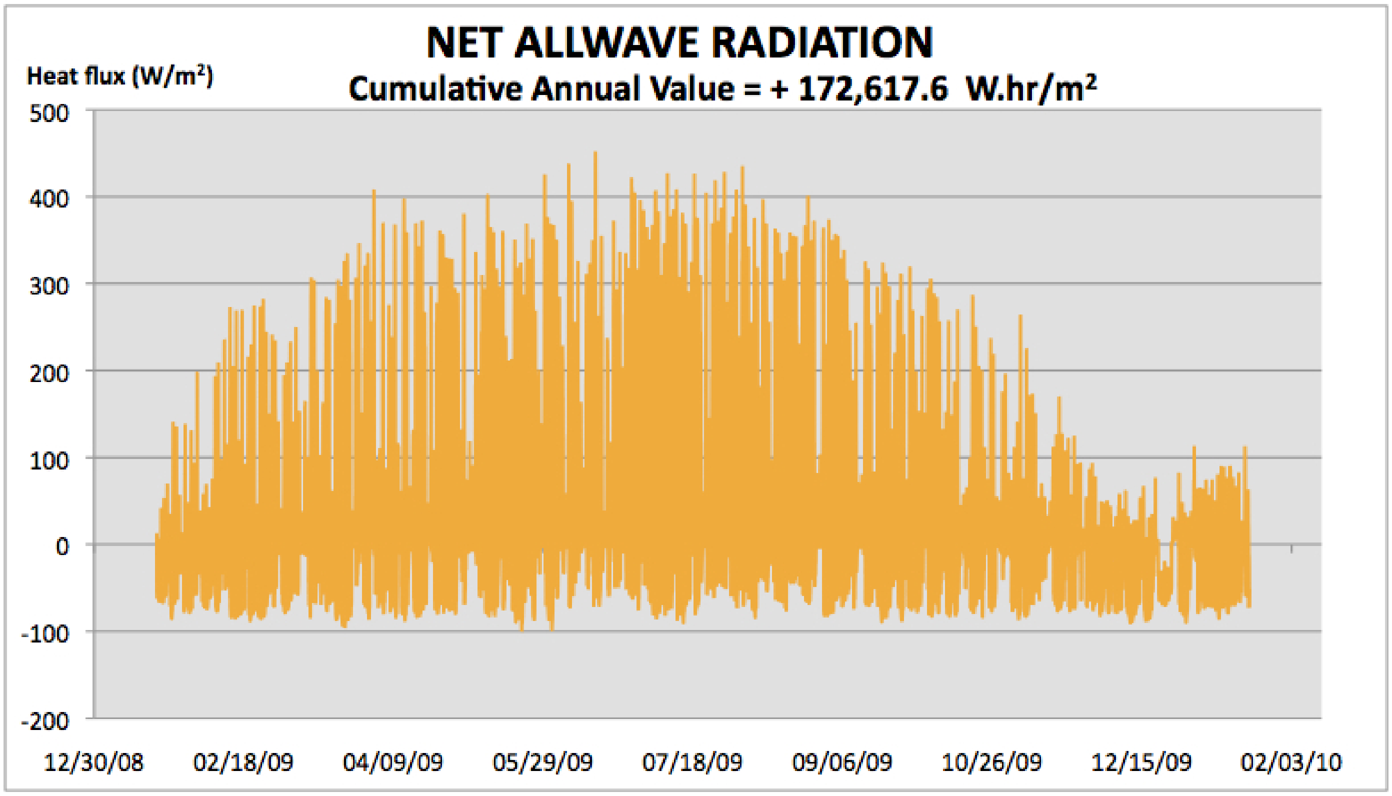

Figure 4. Hourly net radiation absorbed or released at the green roof surface

Like the cumulative water budget, if we consider the energy balance over long periods of time, such as months and years, the cumulative flows of energy across the top and bottom green roof boundaries inevitably grow to large values, while the stored energy remains small and limited. In other words, over the long term, the energy received from radiation must eventually leave the green roof layer as either convective heat, conductive heat, or latent heat:

$$\begin{aligned} &\mathit{cumulative\ radiation} \cong \\ &\qquad \mathit{cumulative\ conduction} + \\ &\qquad\qquad \mathit{cumulative\ convection} + \\ &\qquad\qquad\qquad \mathit{cumulative\ latent\ heat}\ (2) \end{aligned}$$

Simply put, there is no place within the green roof that energy can accumulate significantly over time.

Since the cumulative latent heat is equivalent to water that never enters the drainage system, it represents the retention term that we are seeking in our analysis. Moreover,

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[7] P. Arden, “A Risky Play: Was New York City’s Shift to Artificial Grass a 300 Million Dollar Mistake?” *City Limits*, 34 (2010): 13–59.

if the other three terms in **Equation (2)** are known from data, we can determine this retention. High-precision energy balance monitoring equipment is available and was installed at the project to determine these three terms. In the following sections, we briefly describe the instrumentation and show the time series and cumulative data for radiation, conduction, and convection terms in equation (2). We then show the residual result for latent heat based on **Equation (2)**. We then convert this cumulative latent heat to gallons of water vaporized and compare it to the annual and summer season precipitation on the green roof.

Net Surface Radiation to the Green Roof

In **Figure 1,** one of two instrument stands is visible on the left-hand side. This stand supports a "net radiation" sensor. This instrument provides high-precision data on the net radiation occurring over the green roof surface at highly resolved intervals of time. In terms of the arrows shown in the energy balance diagram in **Figure 3**, this net radiation corresponds to the net value of the two surface yellow and two surface red arrows shown. A positive value means net radiation is being absorbed by the roof, while a negative value means the roof is losing net radiation to the atmosphere. The data are recorded in units of Watts/meter^2 (W/m^2).

A graph of the hourly net radiation data for year 2009 is shown in **Figure 4**. The data show a pronounced daily cycle with peak energy absorption during the day when solar energy is at a maximum and a nighttime energy loss when the surface is generally losing thermal radiation to the cooler atmosphere. The daytime peaks show an expected seasonal cycle corresponding again to peak summer season solar radiation.

The cumulative net radiation over the entire year is 172,618 W•hr/m^2. This means that over the year there is a net gain in such energy to the green roof surface. This energy has to appear elsewhere in the green roof system, and as we will show, it is largely being lost from the green roof as latent heat.

Heat Conduction under the Green Roof

Figure 5 depicts the below-grade instrumentation on the green roof that is not visible in **Figure 1**. Two sets of this instrumentation were installed—one set in the northern (sunny) area of the green roof and a second replication in the southern (partially shaded) section of the green roof. A number of sensors are depicted, but the key sensors for this discussion are the two lowest "thermistors" placed above and below a blue layer labeled "insulation board." These two thermistors were strategically placed in direct contact above and below the insulation board (R≅20). This allows a precise estimate of the temperature gradients and, given the thermal resistance of the insulation board (R-value), heat flows through the board and into or out of the

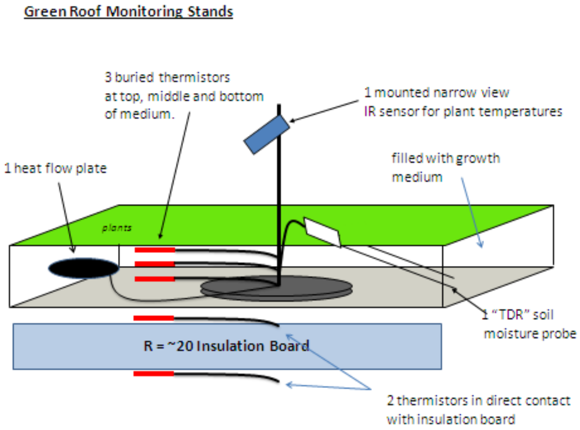

Figure 5. Green roof monitoring equipment below grade

lower boundary of the green roof system.[8] The heat flow determined from this data corresponds to the lower boundary heat flow depicted in **Figure 3**.

Figure 6 shows the hourly conductive heat flow during 2009, as calculated from the insulation board boundary temperatures and its R-value (R=20). The scale for this data is orders of magnitude lower than for the surface radiation data. This is to be expected as peak atmospheric radiation energy is generally much greater than ground or building thermal heat flows.

Positive conductive heat flows correspond to energy entering the green roof layers from below, while negative conductive heat flows correspond to heat loss to the building interiors. As seen in **Figure 6**, such positive heat flows occur in wintertime, meaning the building is generally warmer than the green roof layer so that heat is entering the green roof medium. Negative heat flows occur in summertime, when the hot green roof temperatures are generally warmer than the building temperatures, so that heat flow is downward into the building interior.

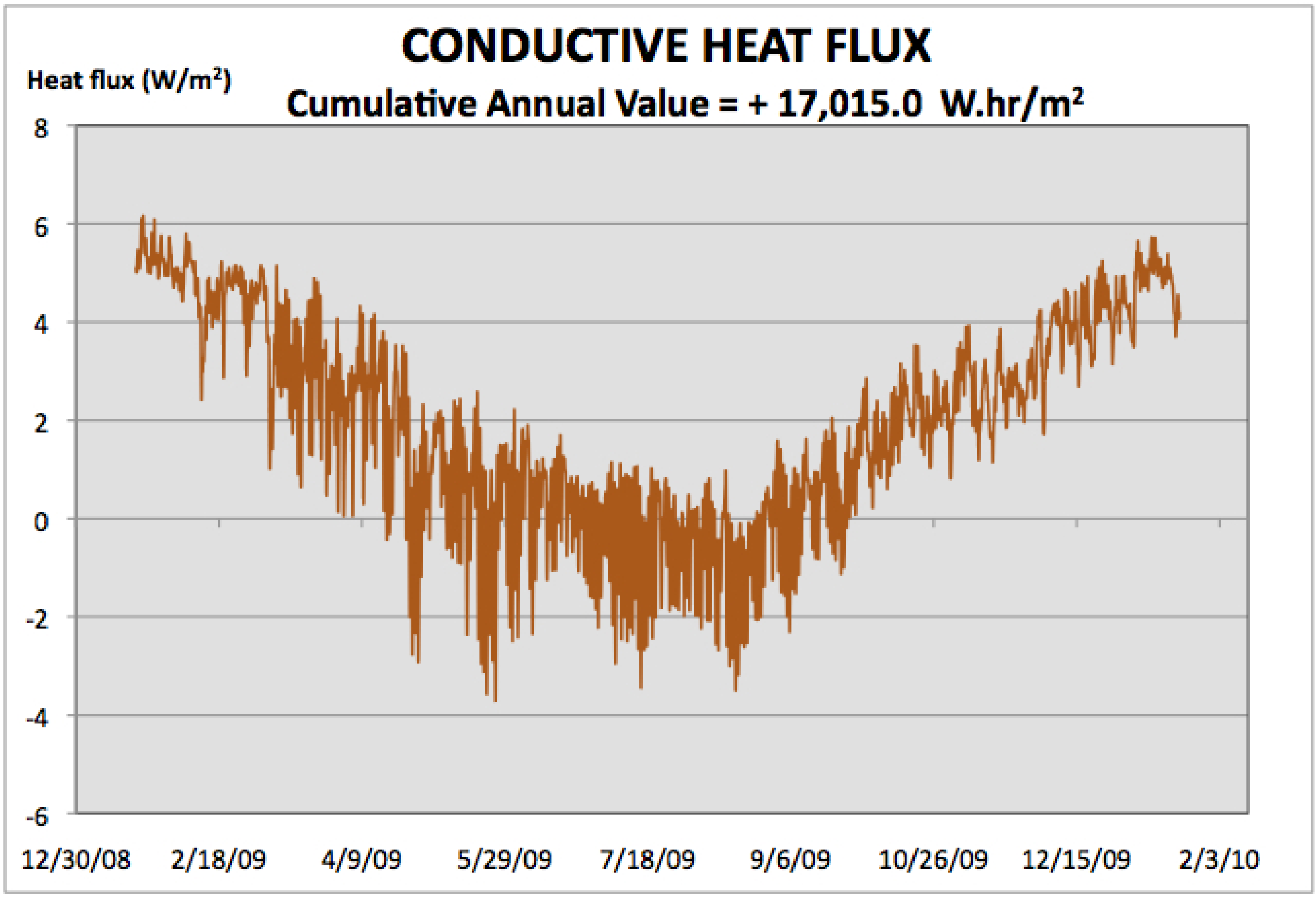

Figure 6: Hourly conductive heat flow into the bottom boundary of green roof layers

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[8] S.R. Gaffin , C. Rosenzweig, J. Eichenbaum-Pikser, R. Khanbilvardi and T. Susca, 2010. “A Temperature and Seasonal Energy Analysis of Green, White and Black Roofs,” Columbia University, Center for Climate Systems Research. New York. 19 pages.

The cumulative conductive heat flux during 2009 was +17,015 W•hr/m^2. This was approximately 1/10 the surface radiation flux. The overall annual heat flux was positive, meaning the green roof had a net gain of energy from conduction. This value quantifies the second of the four energy terms in **Equation (2)**.

Convective Heat Flux from the Green Roof

Convective heat differs fundamentally from latent and conduction heat in that it refers to a transport of mass and an associated heat energy carried by that mass. In a body of water it refers to the movement of parcels of water at a given temperature that are volumetrically replaced by water at another temperature. Similarly, in the atmosphere it refers to the replacement of parcels of air at given temperatures, by different parcels of air at different temperatures. For a roof surface one can envision a boundary layer of air overlying the membrane that has a temperature close to that of the membrane. Movement of this boundary layer of air, due to wind or thermal instability, causes parcels to leave the boundary layer to be replaced by overlying parcels of air of a different temperature.

Mathematical equations for convective heat transport are not as straightforward as for conductive or radiative energy because, in general, the physical process at work is called "turbulence," a chaotic fluid dynamic phenomenon. However, given the importance of the surface temperatures and the overlying air temperatures, as well as wind speed, most formulae involve such temperatures and wind speeds. In this report we use three published formulae for rooftop convection that use such data:

$$Q_{conv\_model\_1} = \begin{cases} \gamma_1 u^{0.8}(T_{roof} - T_{air}) \; if \; u > 1.75 \; m/s \; else \\ \gamma_2 (T_{roof} - T_{air}) \end{cases} \tag{3}$$

$$Q_{conv\_model\_2} = \gamma_3 (T_{roof} - T_{air}) \tag{4}$$

$$Q_{conv\_model\_3} = \gamma_4 (T_{roof} - T_{air}) \tag{5}$$

Formula (3) was published by the author[9] and based on simulations of roof temperatures and energy balances. **Formulae (4) and (5)** are from a published report by other authors[10] using similar energy balance data.

In these formulae, *u* stands for windspeed (meters/sec) and T_{roof} and T_{air} stand for roof surface and air temperatures, respectively. The coefficients $\gamma_{1,2,3,4}$ are empirically determined constants based on fits to temperature and energy data. In **Formulae (4) and (5)**, γ_3 and γ_4 were found to have a range of values from 18 to 25 (Watts/K-meters^2). In this report we present convective heat results for both these upper and lower values of γ.

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[9] S. R. Gaffin, C. Rosenzweig, L., Parshall, D. Beattie, R. Berghage, G., O'Keeffe, and D., Braman, "Energy Balance Modeling Applied to a Comparison of Green and White Roof Cooling Efficiency," in *Proceedings of the 3rd Annual Greening Rooftops for Sustainable Cities Conference,* Washington, D.C., May 4–6, 2005.

[10] P. Berdhal and S. Bretz, "Preliminary Survey of the Solar Reflectance of Cool Roofing Materials," *Energy and Buildings* 25 (1997): 149–158.

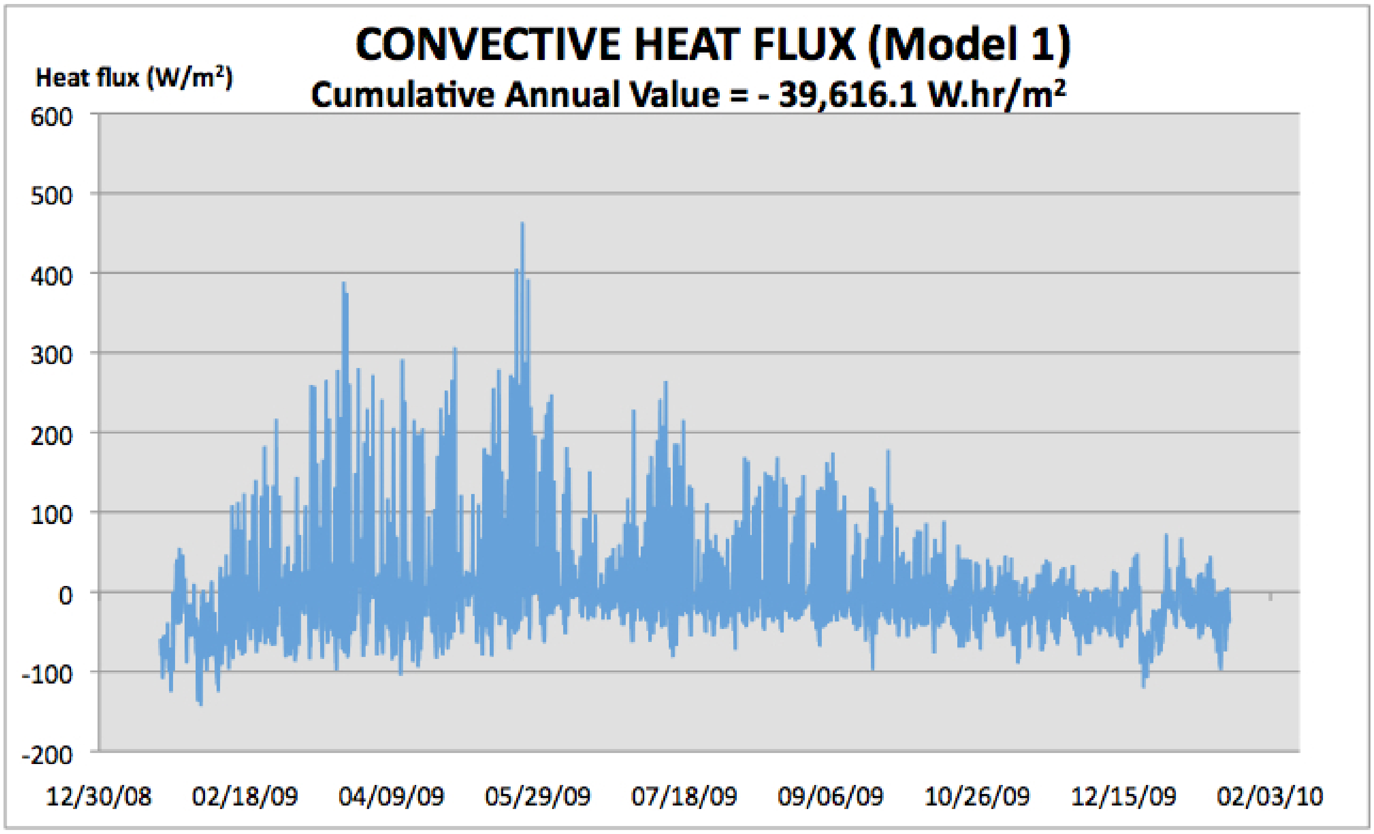

Figure 7. Hourly convective heat flux from the green roof surface to the atmosphere

Windspeed and air temperature data were taken from the weather station visible in **Figure 1** on the right-hand stand and roof surface temperature data were taken from the thermistor and radiometer data depicted in **Figure 5**.

Figure 7 shows the estimated hourly convective heat flow using model 1 and data on windspeeds and roof surface and air temperatures. Positive values are heat losses to the atmosphere, and negative values are heat gains from the atmosphere. In general, the losses are occurring during the daytime, when the roof surface temperatures in sunlight are higher than the air temperatures, so that the parcels of air at the surface carry heat away from the green roof. At night these surface temperatures drop significantly,[11] and the temperature gradient reverses with the air being warmer than the surface, thus warming the surface.

In contrast to the radiative and conductive heat flows shown in **Figures 4 and 6,** the convective heat flow is not as symmetric annually and displays a late winter/early spring peak in daytime losses. This is due to a combination of factors, including the fact that windspeeds in the NY City area are generally highest during these times of the year and also the daytime temperature contrast between the surface and air is large, since sunlight heating of the surface is becoming strong during the spring

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[11] Gaffin et al. “A Temperature and Seasonal Energy Analysis of Green, White and Black Roofs.”

and air temperatures are not yet generally very warm.

The cumulative annual value for these data is -39,616 W.hr/m^2. The negative sum means that overall, the roof was gaining surface energy from the atmosphere due to convection.

Indeed, all the cumulative values from radiative, conductive, and convective heat flow indicate that the green roof was gaining net energy annually from all three processes. Thus there has to be a counterbalancing energy loss term. As indicated by **Equation (2)**, this remaining energy loss term is the latent heat flow, the determination of which is the goal of this report.

Latent Heat Flux from the Green Roof

Equation 2 is strictly correct only when used over long periods of time, as the short-term changes in stored energy may be significant compared to the other heat flows.

In **Figure 8** we show the hourly residual heat changes in the green roof based on adding the hourly values of radiative, conductive, and convective heat flows shown in **Figures 4, 6,** and **7**. In the short term, this residual energy is the sum of latent heat changes and the rate of change of stored energy. Over the long term, the cumulative value of the rate of change of stored energy must remain small compared to the latent heat. Physically, this is because there is no significant internal energy reservoir within the four-inch green roof medium and plants that can continually accumulate energy. The

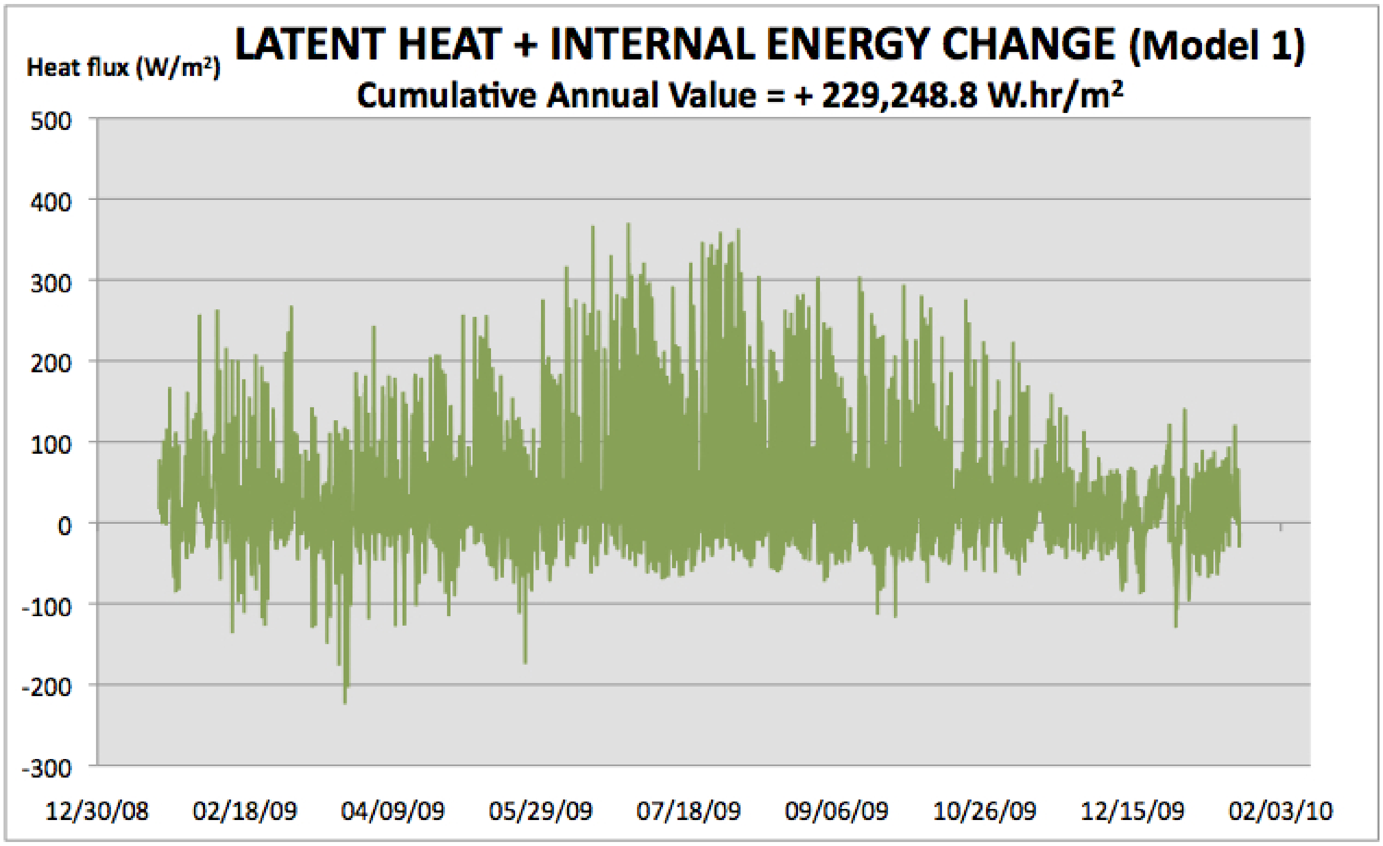


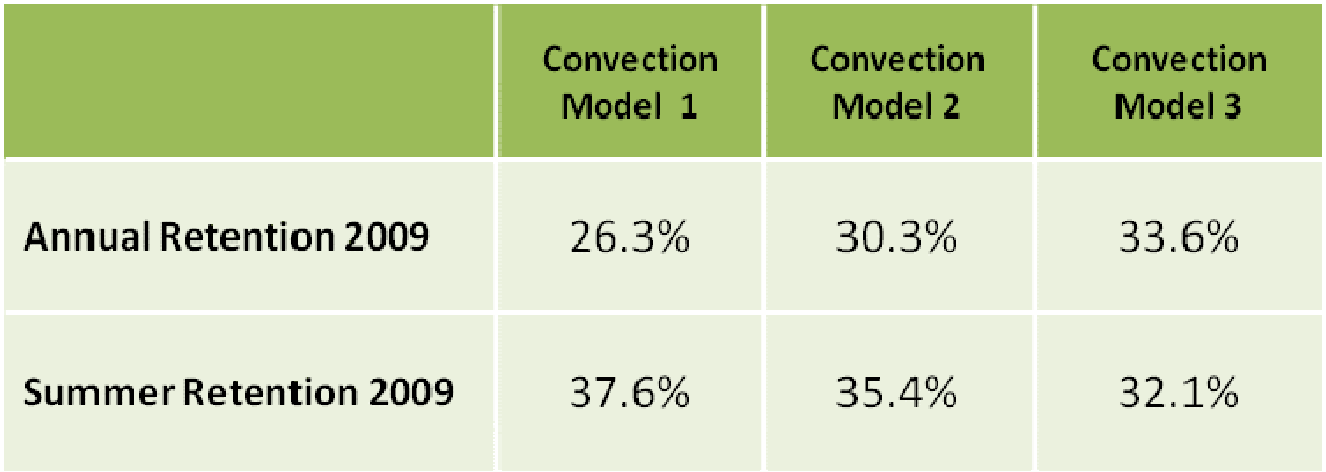
Figure 8: Hourly latent heat flux plus internal energy change rate within the green roof

volumetric mass, water mass, and biomass (for the most part) are not accumulating significantly over time.

That cumulative annual value in **Figure 8** is +229,249 W•hr/m^2. This value is our key estimate for the annual latent heat loss from the green roof. This value is the heat energy content of the water vapor that derived from the liquid soil water in the green roof and left the roof surface.

Conversion to Volume and Percent of Water Retained

The next steps in the analysis require converting the annual latent heat loss (+229,249 W•hr/m^2) derived in the previous section into a physical volume of liquid water and then comparing this to the volume of water that fell as precipitation upon the green roof.



	Convection Model 1	Convection Model 2	Convection Model 3
Annual Retention 2009	26.3%	30.3%	33.6%
Summer Retention 2009	37.6%	35.4%	32.1%

Table 1. Green roof water retention results as a percentage of annual and summertime rainfall

We first convert the annual latent heat energy loss per unit area (+229,249 W•hr/m^2) into a total annual energy loss for the entire roof area of 10,000 m^2. This conversion yields 825,259,935 Kilojoules energy loss for the entire green roof surface area.

We then convert this total energy loss to a *mass* of liquid water using heat of vaporization coefficients. These are well-known thermodynamic quantities dependent on temperature. For example, at 10^{o}C (18^{o}F), the vaporization of 1 kilogram (2.2 lb) of liquid water consumes 2,477 Kilojoules of energy. Using the average annual temperature of the green roof, we calculate from the latent heat of vaporization coefficient that approximately 333,722 kg of water evaporated from the roof surface during year 2009.

This mass of water can easily be converted into a volume of water using the density of water, which has a small dependence on temperature. Again, using the average temperature of the roof, the above mass of water represents approximately 334 cubic meters (m^3).

Finally, we compare the volume of annual evapo-transpired water to the annual incident volume of precipitation (rain, snow, dew, frost) as measured by the rain gauge data from the project. This latter volume was approximately 1,270 cubic meters. Thus dividing 334 m^3 by 1,270 m^3 yields an average annual water retention value of about 26 percent. This result is dependent on the model 1 values for convective heat loss from the roof.

We repeated the above calculations using models 2 and 3 for convection and also restricting the calculation period to summer 2009. **Table 1** summarizes these retention findings.

	Con Edison 4-inch modular	Fieldston 4-inch continous
Roof Age in 2009	1 yr	2 yr
Annual Retention	30.3 %	NA
Summer Retention	35.4 %	~49.7 %
Annual Gallons Retained Per Square Foot	10.2 gal/sf	NA
Summer Gallons Retained Per Square Foot	4.4 gal/sf	6.1 gal/sf

Table 2. Comparison of green roof retention between a modular and built-up (continuous) roof

The three convection models (**Equations 3, 4,** and **5**) produce small percentage differences in the estimated retention, with model 2 yielding what seem to be average values. Based on these figures, we estimate that during 2009 the Con Edison modular green roof system was retaining ~30 percent of incident rainfall annually and ~35 percent of summer rainfall. The roof was therefore detaining approximately ~70 percent and ~65 percent of incident rainfall annually and during summer, respectively. The higher summer retention percentage is no doubt due to the greater biological activity of the plants during the growing season, as compared to the winter periods when the plants are dormant.

Using the roof area and volume of rainfall incident, we also estimate that the roof was retaining 10.2 gallons per square foot annually and 4.4 gallons per square foot during the summer season. Therefore 43 percent (=4.4/10.2) of the annual retention took place during the summer season.

Comparison of Modular and Continuous Green Roof Retention

The Con Edison green roof is a 4-inch sedum modular system. We are currently monitoring a continuously layered 4-inch sedum system at another site (the Fieldston School) in New York City.[12] A previous study[13] has quantified the

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[12] S. R. Gaffin, R., Khanbilvardi, and C. Rosenzweig, "Development of a Green Roof Environmental Monitoring and Meteorological Network in New York City," *Sensors* 9 (2009): 2647–2660; doi:10.3390/s90402647.

summer retention on that roof as ~49.7 percent and 6.1 gallons per square foot during 2009. **Table 2** summarizes the comparison. Thus the data suggest the modular system may be retaining water a lower rate. This could be due to the existence of tray boundaries and gaps between modular units, which probably offers overall less medium volume for retention. In addition, the tray boundaries may be restricting horizontal flow and effectively shunting water more quickly to the drainage layer.

It should be noted that these retention figures are long-term averages of annual and seasonal time-frames. The retention performance of green roofs varies greatly for individual storm events. Due to the energy balance approach taken here, we are not able to use this data to study short-term events. As a reference point, however, the Fieldston School study of the continuous system cited above[14] found that retention during individual storm events varies from 0 to 100 percent. In other words, during some storm events, the green roof showed no retention, while during others it had 100 percent retention or no runoff. This can be explained largely by different antecedent conditions on the roof, where during dry periods the ability to absorb and hold rain is much greater than during wet periods, where the medium has a high soil moisture content.

Cost-Effectiveness of Modular Green Roof Stormwater Retention

The data in **Table 2,** combined with project cost estimates, allow us to examine assumptions made in the "PlaNYC Sustainable Stormwater Management Plan 2008" (PlaNYC 2008), which evaluated the cost-effectiveness of numerous CSO control technologies, including green roofs.[15]

The blue row in **Table 3** shows the assumptions and cost estimates made in PlaNYC 2008 for green roofs. As seen in the column labeled "Gallons retained per sf," PlaNYC assumed only 0.47 gallons per square foot annually. By contrast our central estimate for this retention from Table 2 is 10.2 gallons per square foot -- a factor of 22 increase.

Using this project-based figure, the adjusted cost estimates are listed in the second row of Table 3 and show an annual cost of $0.15 to retain a gallon of water compared to $3.33 in PlaNYC 2008. This correction alone seemingly changes the ranking of green roofs from *least* cost-effective in the PlaNYC report to *most* cost-effective of the stormwater interventions considered in that report.

Moreover other assumptions made in PlaNYC 2008 for green roofs are also questionable and further reduced the cost-effectiveness. One critical number is the annual maintenance cost assumed in PlaNYC of $1.56 per square foot per year maintained for 40 years, as shown in **Table 3**. From our experience with simple 4-inch sedum plant roofs, such a cost per year maintained for 40 years seems vastly too

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[13] K. DiGiovanni, S. R. Gaffin, F. Montalto, and C. Rosenzweig, "Green Roof Hydrology: Results from a Small-Scale Lysimeter Setup (Bronx, NY)," in *Proceedings of Million Trees, Green Infrastructure and Urban Ecology: A Research Symposium*, New York, NY, March 5–6, 2010.

[14] DiGiovanni, "Green Roof Hydrology."

[15] "PlaNYC Sustainable Stormwater Management Plan 2008," The City of New York. Available at: http://www.nyc.gov/html/planyc2030/downloads/pdf/sustainable_stormwater_plan.pdf

	Incremental capital cost per sf	Lifespan (years)	Cost per year per sf	Net present value per sf	Gallons retained per sf	Cost to capture a gallon	Annual cost per gallon
PlaNYC Stormwater Management Report 2008	$24.50	40	$1.56	$62.39[16]	0.47	$133.37	$3.33
Con Edison Green Roof Project, this study	$20.00	40	$1.56	$57.14	10.2	$5.60	$0.15
			$0.20	$24.76	10.2	$2.43	$0.02

Table 3. Comparison of PlaNYC and this study's cost-benefit estimates for green roof runoff control

high. We are monitoring a number of sedum roofs in New York City and they have generally required minimal and simple weeding maintenance for the first few years, as the plants are very tolerant of drought and temperature extremes. Note that green roof spaces are not meant to be trafficked areas, nor will they require similar maintenance to turf grass fields, such as mowing, fertilizing (in early years), or watering. Moreover, they will be dormant for much of the year during the cold seasons.

We regard a more plausible figure to be closer to $0.20 per square foot, and have assumed this in the third row of **Table 3**. This correction further improves the cost-effectiveness of green roofs and makes it almost an order-of-magnitude better than the other PlaNYC interventions considered, as estimated in that report.

Two other corrections will be mentioned here that would further improve the green roof cost estimates but need not be quantified as they just reinforce the point. A 40-year life span for the green roof was assumed, which is reasonable given the greatly reduced thermal and atmospheric stresses on green roof membranes.[17] However, this also implies that the building owner has avoided at least one roof replacement cost and this financial benefit (at, say $10–$15 per square foot) will increase green roof cost-effectiveness.

Also in PlaNYC 2008 *detained* water for blue roofs was given equal weight as retained water. But green roofs are also detaining water and probably more effectively than blue roofs, given the area and volume of medium that the rainwater is percolating through before it reaches the drains.

Finally, it has been shown in **Table 2** that the modular sedum system we have studied is retaining less water than similar built-up green roofs, which would therefore perform even better.

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[16] The PlaNYC 2008 report assumed a 3 percent discount rate which we use in this table.

[17] Gaffin et al, "A Temperature and Seasonal Energy Analysis of Green, White and Black Roofs."

Concluding Remarks

The stormwater retention calculation presented in this report is based solely on energy and temperature data and uses an "energy balance" approach. The key green roof performance quantity of interest—water retention—also happens to be a central quantity in the energy balance equation, namely, latent heat loss. We exploit this fortuitous fact since high-precision data can be collected to allow all the other terms in the energy balance **Equation (2)** to be determined, leaving retention as a residual.

The two main limitations of the energy balance approach are: (i) it can be easily applied only to long-term data, over time scales where the changes in internal stored energy can be ignored and (ii) it requires estimating the convective heat losses, which can be complex and not as precisely monitored as other energy terms.

The first limitation simply means that the details during individual storm events are not revealed by the method. Still, long-term retention is an equally important estimate for urban stormwater management considerations. We have addressed the second limitation by considering a few models for the convective heat flows on the green roof.

With these caveats, it is of scientific and practical interest to see the estimates based on energy balance. In field and remote sensing applications, such as for agricultural and natural settings, the energy balance approach is routinely applied to estimate components of the water budget, including evapo-transpiration.[18] We are unaware of a similar application to green roofs before this report.

Our results show that the latent heat term on the Con Edison green roof was the only net annual heat loss process for the green roof layer. All the other fluxes added net heat annually to the layer. After converting this heat loss to a volume of water, we find that the green roof is retaining approximately 10 gallons of water per square foot annually. This is significantly lower than the retention found on a similar 4-inch sedum green roof that has a continuous medium layer rather than a modular system. The lower retention may be due to the technological difference that there is less medium volume overall and less horizontal water flow because of tray boundaries.

In terms of urban stormwater management and combined sewage overflows, such retention adds up to an impressive total when the urban roofscape is considered. Assuming New York City has at least 1 billion square feet of roof area that could in principle be greened, we estimate that annual stormwater flow to the City's wastewater treatment facilities would be reduced by at least 10 billion gallons. Moreover the water that does run off will be detained and thus have a secondary positive effect on CSO mitigation. In addition, the cumulative green surfaces will have synergistic positive impacts on urban heat island, building energy and urban ecology.

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[18] W. P. Kustas and J. M. Norman, "Use of Remote Sensing for Evapotranspiration Monitoring over Land," *Hydrological Sciences Journal* 41(4) (1996): 495–516.

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